V.

CONTRIBUTIONS FROM THE PHYSICAL LABORATORY OF THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

XXXV. — ON THE EXTENT OF THE EXCURSION OF THE ELECTRODES OF A MICROPHONE TRANSMITTER.

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The character and extent of the motions of the electrodes of a microphone transmitter, when actuated by sound-waves of different degrees of intensity, is a subject in telephony of by no means slight importance, but to which very little study has been given. The present paper describes the results of some observations relating to this subject, which have been made at various times during the past two years.

Several years ago an attempt was made by Mr. W. W. Jacques and the writer to gain some knowledge as to the amplitude of the vibrations of the hammer electrode of a microphone, by observing it with a microscope while in operation, and noting the extent of the blurred portion of the image. The results, though giving all that could be expected from so crude a method, were not very satisfactory so far as definite measurement was concerned.

It afterwards occurred to the writer that the matter might be studied more completely by the use of the stroboscopic method, and an arrangement of apparatus was adopted by which the motions of the electrodes could readily be observed.

This was done in the following manner. The microphone to be studied was placed in the field of a microscope, whose line of collimation was horizontal. Behind the microphone, at a suitable distance, was placed a Helmholtz mercury interrupter, with a tuning-fork making 128 vibrations per second. The extra current due to the electromagnets of the interrupter was quite large, so that a brilliant spark was obtained at each rupture of the circuit, as the platinum style of the interrupter left the mercury. The interrupter being properly placed,

and the light of the spark concentrated by a lens, quite a bright field was obtained, against which the electrodes were seen projected, as silhouettes. The light, though intermittent, of course seemed continuous, since the sparks were so numerous. When good definition was obtained, the microphone was set in operation, usually by means of an organ-pipe placed at a convenient and variable distance, and in some experiments by the voice. The pipe was blown by a constant blast, and great uniformity of intensity in the sound was secured. An open C_3 organ-pipe making approximately 256 double vibrations per second was commonly used, its pitch being variable to a moderate extent by shading the mouth or the opening at the top.

So long as the pipe was an exact octave in pitch above the interrupting fork, the electrodes of the microphone as seen with the microscope appeared to be at rest; but if the interval was slightly disturbed, the stroboscopic effect was observed, and the electrodes seemed to move slowly through their complete course. The rate of this apparent vibration was of course dependent upon the deviation of the pipe from exactness in its interval with the fork, and could be varied at will within quite wide limits.

The extent of the motion of the electrodes could be determined by observing the grains of dust which adhered to them, or some definitely marked roughness on their surface. Measurements were made by means of a spider-line micrometer, the wires of which were placed at a convenient distance apart, and the amplitude of the motions of the selected points of reference on the microphone was determined by estimating the relation of their apparent motion to the distance separating the wires of the micrometer. This last distance was frequently varied to diminish the liability to error from a possible bias of the observer towards an agreement with earlier results.

In the experiments described in the present paper, the electrodes were generally so adjusted that the motion of the anvil electrode was too small to be observed. Under these circumstances the observed motion of the hammer electrode, as measured by the micrometer, was the motion of this relatively to the anvil electrode, which is of course the quantity to be determined, rather than the actual excursion of the hammer electrode.

The microphone was placed in circuit with a battery and the primary of an induction coil, whose secondary contained a receiving telephone. With this arrangement the effect on the ear of the electrical variations due to the various values of the excursions of the electrodes could readily be observed. In many cases a second observer was sta-

tioned at the receiving telephone, which was then placed in a separate room.

Magnifying powers were used of from 50 to 1,000 diameters. With the higher powers the use of an objective of short focal length was difficult on account of the small working distance, so that, although even as short a focus as $\frac{1}{10}$ in. was sometimes employed, it was found much preferable to obtain the needed magnification by the use of short focus eye-pieces.

The brilliancy of the electric spark was amply sufficient for illumination of the field, even with the highest magnification employed; a fact which calls attention vividly to the enormous "instantaneous intensity" (so to call it) of that light. Considering the excessively brief duration of the spark and the very small quantity of matter illuminated, it seems unquestionable that the intrinsic brilliancy is far greater than that of the electric arc, a view fully supported by the results of spectroscopic study.

Various forms of microphone were observed, but the general features characterizing the actions studied were common to them all. As the intensity of the sound acting on the microphone was increased by approaching the organ-pipe to the diaphragm, the motion of the hammer electrode, at first absolutely invisible, was seen gradually to increase, until, when the intensity was very great, the motion was excessive, the anvil electrode being violently pushed aside, and the hammer leaving it on its return motion, so that the circuit was broken at every vibration. At the same time bright sparks were seen between the electrodes. To the ear the simultaneous acoustic changes in the sound transmitted were very striking. The sound of the pipe was distinctly audible, and its quality clear, with motions of the hammer electrode far too slight to be observable. As the sound actuating the telephone became louder, and the excursion of the electrode became visible, the quality continued good, the sound transmitted growing louder; and then, as the excursion increased further, the quality gradually changed, shrill false notes made their appearance, and the sound began to grow harsher, until finally, when breaks appeared in the current, the sound was excessively harsh, and entirely devoid of musical quality. Long before this, however, the characteristic quality of the organ-pipe disappeared.

The following tables will illustrate the results obtained. In making many of the measurements I worked in company with Mr. W. W. Jacques, whose observations were always in substantial accord with my own. A large number of observations have also been made, under

my direction, by Messrs. A. W. Jones and F. L. Dame, students in the Laboratory, whose work has been performed with conscientiousness and accuracy.

The microphone used in most of the experiments was one in which the anvil electrode was a "pendulum electrode," suspended by a vertical rod, hinged at the top, and so weighted as to give to it a proper mass. The desired normal pressure could be obtained by sliding the point of suspension laterally so as slightly to incline the supporting rod, and further, by adding a weight so as to exert a proper leverage, if this was desired. The hammer electrode was pointed and carried by the diaphragm, which was of mica. The sounding pipe was gradually removed from or approached toward the microphone. Care was in all cases taken to keep the wind pressure constant. A single Leclanché cell was ordinarily used, though in a few cases a Grénet cell was employed.

In the various tables, the excursions of the electrodes are in all cases given in fractions of an inch. In designating the material of the electrodes, that of the anvil is stated first.

Tables I. to III. show the results obtained when both electrodes were of carbon; Tables IV. and V., when the anvil electrode was of carbon, the hammer of platinum. Tables VI. to VIII. contain results of observations made with a modified form of transmitter, in which the anvil electrode was also somewhat heavier than in the earlier experiments.

TABLE I.

ELECTRODES, CARBON, CARBON. — *Magnification, 50 diameters.*

Excursion.	Character of Sound.
1000×10^{-6} to 700×10^{-6}	Constant breaking and sparks. Electrodes visibly separating.
600×10^{-6}	Constant sparking. Electrodes occasionally seen to separate.
200×10^{-6}	Occasional breaks and sparks.
200×10^{-6}	Scratchy sound, no sparks.
No visible motion.	Sound clear and smooth.

TABLE II.

ELECTRODES, CARBON, CARBON. — *Magnification, 50 diameters.*

Excursion.	Character of Sound.
1000×10^{-6} to 600×10^{-6}	Constant sparks; electrodes separating.
300×10^{-6} to 200×10^{-6}	Harsh; occasional breaks and sparks.
150×10^{-6}	Scratchy.
No visible motion.	Clear and smooth.

Whenever the excursion of the hammer was greater than 100×10^{-6} the sound was very scratchy and harsh.

TABLE III.

Electrodes, Carbon, Carbon. — *Magnification*, 160 *diameters.*

Excursion.	Character of Sound.
350×10^{-6} to 300×10^{-6}	Loud, noisy, harsh.
250×10^{-6} to 200×10^{-6}	Very scratchy.
120×10^{-6} to 80×10^{-6}	Scratchy, but less than before.
150×10^{-6} to 100×10^{-6}	Scratchy, but with high overtones.

At the lowest amplitude given in Table III. the quality of the sound of the pipe was first heard, but a still less amplitude was necessary for its satisfactory reproduction.

TABLE IV.

Electrodes, Carbon, Platinum. — *Magnification*, 160 *diameters.*

Excursion.	Character of Sound
250×10^{-6}	Constant sparks and breaks.
120×10^{-6}	Scratchy; occasional sparks and breaks.
70×10^{-6}	Raspy.
50×10^{-6}	Quality distinct, but high squealing overtones present.
20×10^{-6}	Quality better; fewer high overtones.
Less than 20×10^{-6}	Quality better; some high overtones still audible.

The pipe had to be carried twice as far away from the transmitter as in last measurement, to a distance of eighteen inches, before the quality became really excellent.

TABLE V.

Electrodes, Carbon, Platinum. — *Magnification*, 150 *diameters.*

Excursion.	Character of Sound.
120×10^{-6}	Very scratchy; occasional sparks.
60×10^{-6}	Squealing, high overtones.
40×10^{-6}	Fair quality; high overtones prominent.
$< 20 \times 10^{-6}$	Good quality; a little rough.
400×10^{-6}	Constant breaking.
60×10^{-6}	Very raspy.
40×10^{-6}	High overtones strong.
20×10^{-6}	Quality good.

TABLE VI.

Electrodes, Carbon, Platinum. — *Magnification,* 700 *diameters.*

Excursion.	Character of Sound.
200×10^{-6}	Rough, but pitch discernible.
80×10^{-6}	Rough, pitch distinct.
30×10^{-6}	Smooth, with high overtones.
30×10^{-6}	" " "
20×10^{-6}	Quality good; some high overtones.
10×10^{-6}	Good quality.
25×10^{-6}	Smooth, with high overtones.
30×10^{-6} to 40×10^{-6}	High overtones prominent.
80×10^{-6}	Harsh and rough.

TABLE VII.

Electrodes, Carbon, Platinum. — *Magnification,* 940 *diameters.*

Excursion.	Character of Sound.
1000×10^{-6} to 800×10^{-6}	Scratchy, with breaks.
100×10^{-6}	Rough, with high overtones.
80×10^{-6}	Wheezy, with high overtones.
40×10^{-6}	Smooth, but with high overtones.
30×10^{-6}	" " "
60×10^{-6}	Rough, with high overtones.
50×10^{-6}	Harsh, with high overtones.
40×10^{-6}	Smoother.
30×10^{-6}	Smoother, with high overtones.
20×10^{-6} to 30×10^{-6}	Good quality, high overtones present.
20×10^{-6}	Good quality.

TABLE VIII.

Electrodes, Carbon, Platinum. — *Magnification,* 940 *diameters.*

Excursion.	Character of Sound.
1000×10^{-6}	Harsh and screamy.
2000×10^{-6}	" "
1000×10^{-6}	High overtones heard; no distinct pitch transmitted.
400×10^{-6}	High strident overtones present.
100×10^{-6}	High overtones still present.
60×10^{-6}	Sound wheezy.
30×10^{-6}	Sound smooth.
20×10^{-6} to 10×10^{-6}	Quality good.

The differences in the effects obtained with a microphone in which both electrodes are of carbon, as compared with one in which one of the electrodes is of platinum, are well known to every one who has

considered the subject. While with the latter it is more easy to produce an actual break of contact between the electrodes than with the former when the sound is increased, on the other hand the quality is much more satisfactorily reproduced, and does not so rapidly disappear on increasing the loudness. These differences were clearly noticed in the observations. Thus for slight excursions of the hammer electrode the quality of the sound with two carbon electrodes was found to be less satisfactory than when the hammer was of platinum, although in the latter case the point of actual breaking of circuit and sparking was usually reached with a less excursion than in the former one. Evidence of these differences appears in the tables just given, and also in those which follow.

It must be observed, that, while the figures given in the tables show what is the maximum amplitude of vibration of the electrodes consistent with the transmission of quality, they entirely fail to indicate the excessive minuteness of the least excursions which are capable of this result. How minute these sometimes are may be inferred from the following observation.

With a microphone having a somewhat heavy anvil electrode, the organ-pipe was gradually moved away from the diaphragm, and the diminishing range of motion of the electrodes noted in the usual manner. When the pipe was at a distance of three inches the motion of the electrodes was too slight to be visible, although this could have been seen readily with the low magnifying power employed if it had been as great as $\frac{1}{20000}$ in. The pipe, still blown with the same loudness, was then carried farther and farther away. At a distance of thirty-six feet, which was the most distant point from the microphone in the room, the sound of the pipe was still distinctly though faintly audible at the receiver placed in circuit with the microphone, and in a distant apartment.

The results shown in the preceding tables give an idea of the phenomena observable with a microphone of the structure employed. Inasmuch as the primary object of the measurements was to obtain some idea of the actual value of the excursion of the electrode, the mass and normal pressure of the electrodes were not particularly considered, except that they were so adjusted as to give good transmission with moderate loudness of the sound actuating the microphone. But it would of course be expected that the numerical value of the relative excursion of the electrodes corresponding to any given character of sound would vary with the mass of the anvil electrode and with the normal pressure between the electrodes. Two separate sets of observations were made to observe the effects of such variations by Messrs.

Jones and Dame. The latter series was somewhat more complete than the former, besides being carried on with better instrumental appliances, and the results hereafter given are taken chiefly from it.

In all experiments of the nature of those under consideration, it is very difficult to get any fixed standard of quality to which to refer such results as the present. Different observers differ to a certain extent in their estimate of the excellence of the quality reproduced. But the point at which the distinctive quality of the transmitted sound disappears is quite well marked, and a very slightly increased vibration of the hammer electrode causes great harshness to result. For this reason, the name "critical point," originally suggested by Mr. Jones, has been given to this limit, and the excursion corresponding to it has been particularly noted, in tests of the varying effects of mass and pressure.

The transmitter used had its anvil electrode suspended like a pendulum, as before. In order to vary the mass without varying the normal pressure, a horizontal wire was suspended beneath the anvil electrode and rigidly attached to it. The middle point of the wire was vertically beneath the point of suspension of the electrode. The masses added consisted of small copper washers weighing 1.1 grams each. By adding two of these whenever the mass was to be increased, and placing one on each side of the middle point of the horizontal wire, the mass of the electrode was increased, while the normal pressure remained substantially constant. In the experiments whose results are contained in Tables IX. to XIII. the normal pressure was exceedingly small, the electrodes always being kept in very light contact. This condition of things was easily secured by a slight adjustment of the position of the washers. A magnification of 280 diameters was usually employed.

The following results were obtained by the mode of procedure just described.

TABLE IX.

ELECTRODES, CARBON, PLATINUM.

Mass in Grams.	Excursion of Hammer at Critical Point.
4.0	12×10^{-6}
8.1	25×10^{-6}
10.3	37×10^{-6}
12.5	50×10^{-6}
14.7	50×10^{-6}
17.0	50×10^{-6}
19.2	50×10^{-6}
21.4	50×10^{-6}

TABLE X.

ELECTRODES, CARBON, PLATINUM.

Mass in Grams.	Excursion of Hammer at Critical Point.
4.8	12×10^{-6}
5.9	25×10^{-6}
8.1	37×10^{-6}
10.3	37×10^{-6}
12.5	50×10^{-6}
14.7	50×10^{-6}
17.0	50×10^{-6}
19.2	50×10^{-6}
21.4	50×10^{-6}
25.8	50×10^{-6}
4.5	12×10^{-6}
8.7	25×10^{-6}
10.9	37×10^{-6}
13.1	50×10^{-6}
17.5	50×10^{-6}
21.9	50×10^{-6}

TABLE XI.

ELECTRODES, CARBON, CARBON.

Mass in Grams.	Excursion of Hammer at Critical Point.
8.5	18×10^{-6}
10.7	18×10^{-6}
12.9	25×10^{-6}
15.1	25×10^{-6}
17.3	25×10^{-6}
19.5	37×10^{-6}
21.7	37×10^{-6}
23.9	37×10^{-6}
28.3	37×10^{-6}

TABLE XII.

ELECTRODES, CARBON, CARBON.

Mass in Grams.	Excursion of Hammer at Critical Point.
5.7	12×10^{-6}
8.7	17×10^{-6}
10.9	25×10^{-6}
13.1	37×10^{-6}
15.3	37×10^{-6}
17.5	37×10^{-6}
19.7	37×10^{-6}

TABLE XII. — *Continued.*

Mass in Grams.	Excursion of Hammer at Critical Point.
5.7	12×10^{-6}
9.1	18×10^{-6}
11.3	37×10^{-6}
15.5	37×10^{-6}
15.7	37×10^{-6}
17.9	37×10^{-6}
20.1	37×10^{-6}

TABLE XIII.

ELECTRODES, PLATINUM, PLATINUM.

Mass in Grams.	Excursion of Hammer at Critical Point.
7.65	12×10^{-6}
9.85	25×10^{-6}
12.05	31×10^{-6}
14.25	37×10^{-6}
16.45	37×10^{-6}
18.65	37×10^{-6}
20.85	37×10^{-6}
7.65	12×10^{-6}
9.85	25×10^{-6}
12.05	37×10^{-6}
14.25	37×10^{-6}
18.65	37×10^{-6}
20.85	37×10^{-6}

An inspection of Tables IX. to XIII. shows that the value of the excursion of the hammer electrode corresponding to the "critical point," and presumably, therefore, the excursion corresponding to any given degree of excellence in the reproduction of quality, at first rises very rapidly as the mass of the anvil electrode is increased, but soon reaches a maximum value, which is not altered by further increase of mass. The rise appears to be less rapid when both electrodes are of carbon than when one or both of them are of platinum, as may be seen by a comparison of the various tables, or, better still, by plotting the results so as to exhibit them graphically by curves. Also, when both electrodes are of carbon or both of platinum, the maximum and permanent excursion at the critical point is considerably less than when the hammer electrode is of platinum and the anvil of carbon, — a fact which goes to explain the well known excellence of a microphone employing these last materials. Further experiment is desirable, however, before fully accepting this explanation. Furthermore, variations in the sur-

face and shape of the electrodes are likely to modify these values to a certain extent. Thus the carbon electrodes used by Mr. Jones gave the results shown in Tables XIV. and XV. The arrangement of the electrodes was as already described, except that the anvil was slightly inclined, and in the second series a weight of bent wire was added to increase the normal pressure by a small amount.

TABLE XIV.

ELECTRODES, CARBON, CARBON.

Mass in Grams.	Excursion of Hammer at Critical Point.
6.5	36×10^{-6}
8.9	50×10^{-6}
11.3	60×10^{-6}
13.7	60×10^{-6}
16.1	60×10^{-6}
18.5	60×10^{-6}
20.9	60×10^{-6}
23.3	60×10^{-6}
25.7	60×10^{-6}

TABLE XV.

ELECTRODES, CARBON, CARBON.

Mass in Grams.	Excursion of Hammer at Critical Point.
2.9	20×10^{-6}
5.3	30×10^{-6}
7.7	40×10^{-6}
10.1	55×10^{-6}
12.5	60×10^{-6}
14.9	60×10^{-6}
17.3	60×10^{-6}

In connection with the various preceding tables the following results obtained by Mr. Jones will be of interest.

TABLE XVI.

ELECTRODES, CARBON, PLATINUM.

Series.	Magnification.	Excursion for Good Quality.	Excursion at Critical Point.	Excursion for Breaking.
1	400	16×10^{-6}	60×10^{-6}	80×10^{-6}
2	400	20×10^{-6}	$30\text{–}40 \times 10^{-6}$	60×10^{-6}
3	400	30×10^{-6}	50×10^{-6}	80×10^{-6}
4	350	30×10^{-6}	60×10^{-6}	80×10^{-6}
5	700	40×10^{-6}	60×10^{-6}	80×10^{-6}
6	1000	30×10^{-6}	70×10^{-6}	80×10^{-6}

In series 2 the normal pressure was slightly less than in the others. The excessively high value of 40×10^{-6} at which in series 5 good quality still persisted, is the highest that has been observed. The hammer electrode had been brought to a sharp point just previously.

I have observed, among the four persons who have employed the method under consideration, that each one has apparently his own standard of what constitutes good quality, and usually adheres quite closely to this in different experiments. The observer last cited generally gave somewhat larger values to the excursion for a given degree of excellence of transmission than I noted in my own observations, apparently from this cause.

A further series of measurements was made in order to ascertain what effect was produced by a variation in the normal pressure between the electrodes.

In order to do this, a wire was caused to project backward from the anvil electrode, and small weights were hung upon the end of it. The pendulum electrode with this projecting wire constituted a bent lever whose arms were easily measured, thus enabling the normal pressure due to a given weight to be calculated. It was thus obtained very easily, although the method is subject to the objection that there is a certain variation of the mass of the anvil electrode simultaneously with the variation in pressure. The use of a delicate spring instead of the weight would be preferable, but I have not yet found time to carry through observations by this method. The results reached are shown in Tables XVII. to XIX.

TABLE XVII.

ELECTRODES, PLATINUM, PLATINUM.

Normal Pressure in Grams.	Excursion of Hammer at Critical Point.
0.34	8×10^{-6}
0.77	14×10^{-6}
1.20	25×10^{-6}
1.63	37×10^{-6}
2.06	50×10^{-6}
2.50	61×10^{-6}
0.34	10×10^{-6}
0.77	12×10^{-6}
1.20	25×10^{-6}
1.63	37×10^{-6}
2.06	50×10^{-6}
2.50	61×10^{-6}
2.93	61×10^{-6}

TABLE XVIII.

ELECTRODES, CARBON, CARBON.

Normal Pressure in Grams.	Excursion of Hammer at Critical Point.
0.297	8×10^{-6}
0.632	12×10^{-6}
0.990	12×10^{-6}
1.288	12×10^{-6}
1.650	25×10^{-6}
2.150	25×10^{-6}
0.272	8×10^{-6}
0.616	25×10^{-6}
0.960	37×10^{-6}
1.304	37×10^{-6}
1.648	37×10^{-6}
1.990	37×10^{-6}

TABLE XIX.

ELECTRODES, CARBON, PLATINUM.

Normal Pressure in Grams.	Excursion of Hammer at Critical Point.
0.184	8×10^{-6}
0.288	12×10^{-6}
0.432	12×10^{-6}
0.632	12×10^{-6}
0.990	12×10^{-6}
1.288	12×10^{-6}
1.654	Anvil vibrating.
0.104	$>8 \times 10^{-6}$
0.132	$>8 \times 10^{-6}$
0.153	8×10^{-6}
0.184	8×10^{-6}
0.288	12×10^{-6}
0.632	12×10^{-6}
0.990	12×10^{-6}
0.180	8×10^{-6}
0.395	12×10^{-6}
0.620	12×10^{-6}
0.644	12×10^{-6}
0.149	8×10^{-6}

It appears from these results, that the value of the excursion corresponding to the critical point rises with increase of normal pressure, soon attaining a maximum and constant value. The pressure at which this maximum value was reached was greatest when both electrodes were of platinum, and least when the hammer electrode was of platinum and the anvil of carbon. When both electrodes were of carbon,

the value lay between these two extremes. The unexpected result was also reached that the value of the maximum excursion was much greater when both electrodes were of platinum than when both were of carbon. It was least when the hammer was of platinum and the anvil of carbon.

A series of observations was also made upon the microphone of the Blake transmitter. These presented considerable difficulty on account of the construction of the parts of that instrument, and only a low magnification could be used. Three sets of measurements were taken, the first with a very light normal pressure, the second with the ordinary pressure, and the third with a very heavy pressure. With this microphone in its proper condition, both electrodes moved. It was therefore necessary to subtract the excursion of the anvil electrode from that of the hammer, in order to obtain their relative motion. The results reached are given in Table XX. The total excursion of the hammer electrode, and its motion relative to the anvil, are given as nearly as they could be measured.

TABLE XX.

BLAKE TRANSMITTER. — ELECTRODES, CARBON, PLATINUM.

a. *Light Normal Pressure.*

Total Excursion.	Relative Excursion.	Character of Sound.
	$< 25 \times 10^{-6}$	Good quality, very faint.
50×10^{-6}	25×10^{-6}	" " clear.
100×10^{-6}	50×10^{-6}	Overtones strong.

b. *Medium Normal Pressure.*

Total Excursion.	Relative Excursion.	Character of Sound.
	$< 25 \times 10^{-6}$	Good quality, very faint.
75×10^{-6}	25×10^{-6}	" " clear.
100×10^{-6}	50×10^{-6}	Overtones strong.

c. *Heavy Normal Pressure.*

Total Excursion.	Relative Excursion.	Character of Sound.
	$< 25 \times 10^{-6}$	Good quality, very faint.
100×10^{-6}	25×10^{-6}	" " clear.
150×10^{-6}	50×10^{-6}	Overtones strong.

These results, although of only approximate exactness, are interesting, as they show one cause of the excellence of the Blake transmitter in practice, in that the mode of support of the electrodes allows of very considerable variations in the absolute motions of both of them without material change in their relative motions.

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